Advanced Reactor Antineutrino Detector Development

Antineutrinos from nuclear reactors continue to play a varied and important role in our understanding of the physics of neutrinos. Recent re-analyses of short-baseline reactor neutrino experiments have revealed a possible discrepancy between observations and the predicted antineutrino flux [1, 2] that may be explained by sterile neutrino states with mass splittings of the order of $\sim 1\text{eV}^2$ and oscillation lengths of $\mathcal{O}(3\,\text{m})$ [3]. Present km-baseline neutrino oscillation experiments would benefit from improved knowledge of the absolute neutrino flux [4–6] and recent work using neutrino detectors in the context of nuclear safeguards opens up the possibility of remote monitoring of nuclear activity. New precision measurements of the reactor antineutrino flux, energy spectrum, and the spectral change as a function of distance are thus well motivated.

Carrying out such measurements, however, holds special challenges that will require the development of improved detector technology. Typical sites at short baselines have little to no overburden and will require the operation of detectors close to the reactor core where both fast-neutron and neutron-capture backgrounds are high. Neutron and muon fluxes through an unshielded detector are expected to be several orders of magnitude higher than the neutrino detection rate. Fast neutrons below a few MeV and thermal neutrons can be sufficiently suppressed with careful passive shielding design. For example, a factor of 10^{-6} suppression of neutrons at 1 MeV can be attained with roughly 24 inches of polyethylene, while hermetic boron-loaded shielding eliminates thermal neutrons. Optimization of such shielding based on GEANT and MCNP is currently underway. Neutrons at higher energies and cosmic muons, however, cannot be easily shielded. Thus, background suppression will likely be the primary technical challenge in the design of the detector. Segmentation, combined with an active muon veto system, can reduce muon backgrounds, however the primary approach to this problem will be reliable event identification, either through the use of a delayed neutron capture signal combined with pulse shape discrimination (PSD) or event track reconstruction.

Electron antineutrinos are typically detected via the inverse-beta interaction $\bar{\nu}_e + p \rightarrow e^+ + n$. By doping with an isotope with a high neutron capture cross-section and requiring a coincidence between the initial neutrino scattering event and subsequent neutron capture, tens of microseconds later, backgrounds can be dramatically reduced. Metal-loaded scintillators based on Gadolinium have been the state of the art in reactor $\overline{\nu}_e$ experiments [7]. However, the high energy gammas in their final states are deeply penetrating, and can create difficulties for accurate position reconstruction in small to medium sized detectors. The development of metal-doped water-based scintillators (WbLS) [8] offers attractive alternatives with different characteristics. Significantly, Li-doped scintillators [9], through the reaction ${}^6\text{Li} + n \rightarrow t + \alpha + 4.8\,\text{MeV}$, may be used to improve on neutron detection efficiency and, being highly localized in the detector, can lead to precise position reconstruction. In addition, recent work with Li-doped plastics has shown significant promise [10]. The choice of these scintillators will be driven by the timing of the delayed coincidence signal, the accidental background suppression, the energy response, and possible veto efficiency against muons. A detailed characterization of these options that addresses, in particular, the potential of PSD is needed.

To meet this need several efforts are underway. A novel technique for neutron time of flight has recently been tested at the National Institute for Standards and Technology that makes use of spontaneous fission neutron sources. Each spontaneous fission emits both neutrons and gammas. By detecting both of these coincident emissions, it is possible to create a time of flight apparatus that simultaneously measures the response of a detector to both neutrons and gammas. A prototype of this technique has been successfully operated at NIST with both ${}^{252}\text{Cf}$ and ${}^{248}\text{Cm}$. In addition, full characterization of WbLS light transport properties, e.g. attenuation length, is also underway. Finally, the National Institute of Standards and Technology (NIST) [11], Oak Ridge National Laboratory (ORNL) [12], and Idaho National Laboratory (INL) [13] all have sites available that can be used for the testing of prototype detectors *in situ*. These measurements, combined with detailed detector simulations also in progress, will allow a full optimization of detector geometry and scintillator choice given a particular set of detector requirements for either short-baseline or safeguards applications.

An alternative approach to event-by-event particle identification is being developed by the mini-Time-Cube collaboration. mini-Time-Cube is a portable directional anti-neutrino detector, that makes use of ultra-fast electronics to reconstruct particle trajectories within a scintillating medium based on light wave-front reconstruction. In principle, this method is scalable to cubic meter scale detectors. A mature prototype is expected to be tested this year.

Recent developments in metal-doped scintillator technology hold the promise of greatly improving background rejection in a high-background short-baseline reactor neutrino oscillation experiment. Full event reconstruction through light wavefront reconstruction is also well under development, and both programs have well defined R&D efforts underway.

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